# Power Distribution System for Robotics Applications

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***Abstract*—Mobile robots are powered nearly exclusively by batteries, commonly with 48 V bus voltage and expected to increase. However, existing power distribution (PD) methods are often unable to cope with high input voltages, varying power requirements and fast transients, resulting in significant power losses. Solving this problem is critical to improving system efficiency. In this paper, a new circuit topology designed for power distribution in mobile robots is presented. The proposed design includes a multiphase buck converter with a power controller that provides six output channels for different loads, all integrated on a printed circuit board (PCB). The converter can handle voltages of up to 100 V and an output power of up to 67.5 W, minimizes output current ripple and effectively controls transient response. In addition, the power controller provides independent activation/deactivation for each output channel. Measurements have shown that the output voltage ripple with a multiphase buck converter is reduced by 35.2 % compared to a single-phase buck converter. The developed circuit topology is encouraging for wider implementation in mobile robotic systems with higher input voltage requirements in future applications.**

***Index Terms*—Power Distribution, PD, Mobile Robot, Multiphase-Buck Converter, Power Controller**

## I. Introduction

IN todays world there are so many aspects which have to be considered in developing a power distribution architectures for mobile robots, and it's getting more and more complex. This is due to the increase of power demand and the dynamic load requirements such as CPUs, GPUs, motor drives, sensors, communication systems and AI processors. In addition to the high current transient behavior $\frac{di}{dt}$, some power distribution architectures are not able to settle down quickly due to load steps and have to deal with high overshoots and undershoots. This could than have a negative impact to the load or even worse it could damage the load. [1] [2]

A number of energy management systems have already been developed in the industry to meet some requirements. One of the first power architectures is the centralized power architecture (CPA). Centralized power architectures are characterized by a single point where power conversion from the input source (AC or DC) to a stable DC output occurs. As the number of different voltage levels increase, CPAs losses increase and over all efficiency decrease. The decentralized/distributed power architecture (DPA) was developed to improve losses and to be more flexible. DPA is typically sourced by a DC voltage and converts the high voltage down to the required voltage close to the load. Nowadays, the semiconductors and the technology have further been improved, the supply voltages of the loads decrease and the current consumption increases. Also, the input voltage grows further from 48 V to 72 V and even more. Therefore, the intermediate bus architecture (IBA) is invented. A common way is to transform the 48 V down to an intermediate stage of 12 V and then further to the point of loads (PoL). In figure 1 a common power distribution system for robotics applications from Vicor Power is depicted. [2] [3]

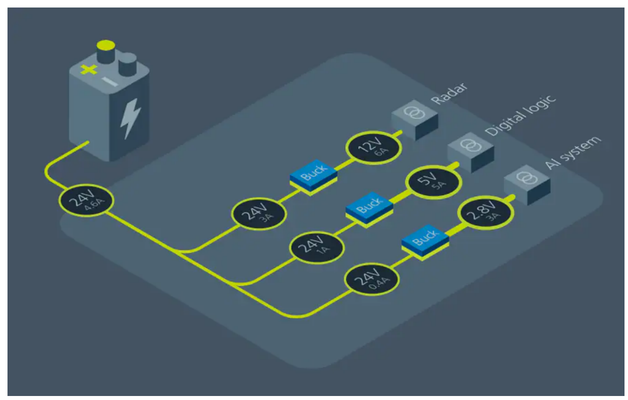


Fig. 1: Power delivery network from Vicor Power [4]

The structure of the paper is as follows. In section II the technological background of power architectures is given. Section III shows the designed power distribution system. The results are described in IV, followed by the conclusion in section V.

## II. Technological Background

### A. Centralized power architecture

In the context of power supply design, centralized power architectures hold a relevant place due to their simplicity, cost-effectiveness, and efficiency. Here the power conversion happens in one central housing. The CPA is supplied either with a battery or with the grid which than has to be rectified to a DC voltage. The distribution for the different power levels occur locally inside the box. In figure 2 a common centralized power architecture is shown which is supplied with a 48 V battery. [5] [6] [7]

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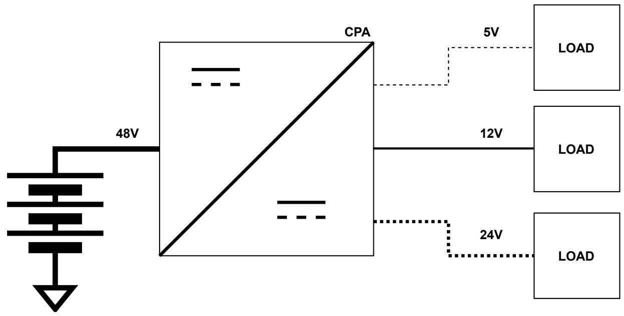



Fig. 2: Centralized power architecture [7]

### B. Decentralized power architecture

Distributed power architecture (DPA) also known as decentralized power architecture is a power distribution strategy widely used in modern electronics, particularly in systems requiring high efficiency and reliability such as telecommunications, data centers, and industrial applications. [5] [6] [7]

The system starts with a primary power source, which could be an AC grid supply or a high-voltage DC supply like a battery. This primary source is distributed across the system to smaller, localized power converters known as point-of-load (PoL) converters. These PoL converters step down the voltage to the required levels and are located close to or integrated with the loads they power. This ensures efficient and precise power delivery. Advanced control systems monitor and regulate the power delivered to each load, ensuring optimal performance and protecting against overcurrent, short circuits, overtemperature, and over- and undervoltage. A standard DPA is depicted in figure 3, which has several PoLs in parallel for different voltage levels. The main supply voltage for all point of loads is a $48\,\mathrm{V}$ battery. [7] [8]

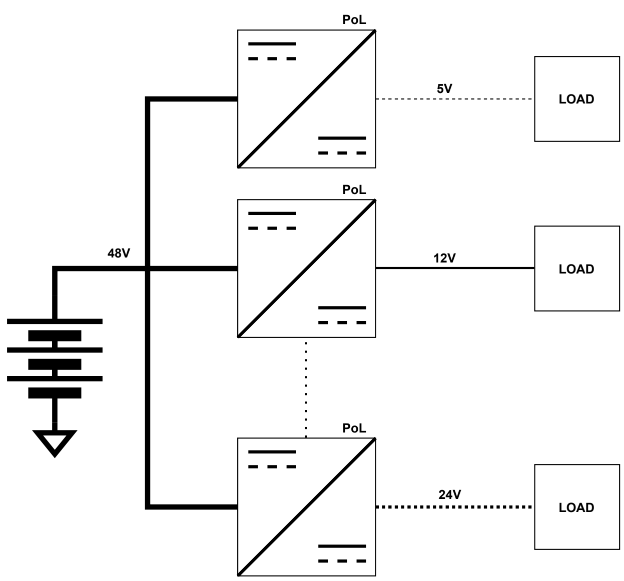



Fig. 3: Decentralized power architecture [7]

### C. Intermediate bus architecture

Intermediate bus architecture is a power distribution method wherein an intermediate voltage level is established between the main power source and the PoL converters. This intermediate voltage is typically higher than the final PoL voltages but lower than the main source voltage. The primary function of the IBA is to step down the primary voltage to a stable intermediate level using an intermediate bus converter (IBC), which then feeds the PoL converters scattered across the system. [7] [9] [10]

Figure 4 represents an intermediate bus architecture with the intermediate bus converter (IBC), and multiple PoLs, providing different output voltages.

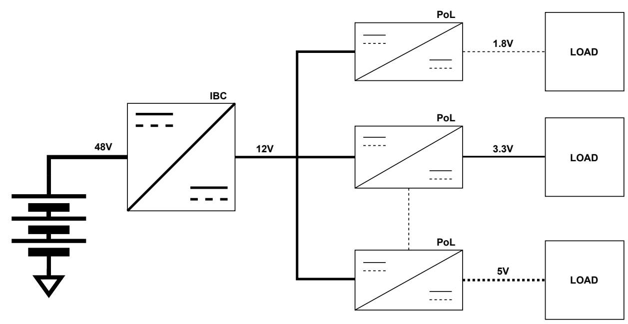



Fig. 4: Intermediate bus architecture [7]

### D. Comparison of power architecture

In this section, the comparison between the three power management architectures CPA, DPA and IBA is discussed and is listed in table I. The criteria are:

- PCB size,
- transient response,
- output voltage ripple,
- scalability and
- heat transfer.

The centralized power architecture would be a good choice for applications where the input voltage is at a level of $24\,\mathrm{V}$ and the output voltage is at least $5\,\mathrm{V}$. The transfer ratio (*tr*) would then be approximately 5:1, which is perfect to have low losses.

If the input voltage is high, e.g. $48\,\mathrm{V}$ or $72\,\mathrm{V}$, and the output voltage is still $5\,\mathrm{V}$, the transfer ratio is approximately 10:1 or 14:1. The duty cycle for the DC/DC converter is very low, which increases the losses and reduces the overall efficiency.

The decentralized power architecture shows the same behavior in the transfer ratio. The only difference is that the DC/DC converters are located close to the load, which reduces losses. Nevertheless, this is not the best solution.

For this reason, an intermediate bus architecture is the best choice for this power distribution system.

Figure 5 shows the radar image for the different architectures. The solid line is the centralized power architecture, the dotted line is the decentralized power architecture and the dashed line is the intermediate bus architecture. The radar

TABLE I: Comparison of power architectures

| Architecture | Advantage | Disadvantage |
|---|---|---|
| CPA | easy design<br>fewer points of failure<br>costs | rigid<br>inefficient<br>high losses |
| DPA | scalability<br>efficiency | high initial costs<br>complex design<br>high rated components |
| IBA | scalability<br>efficiency<br>size<br>heat transfer | complex design<br>high initial costs<br>potential points of failure |

plot shows in which criteria the different architectures are very good and in which they are not. If the line is close to the center, this shows that the power management architecture could be improved, if the line is on the outside, this means that it is very efficient.

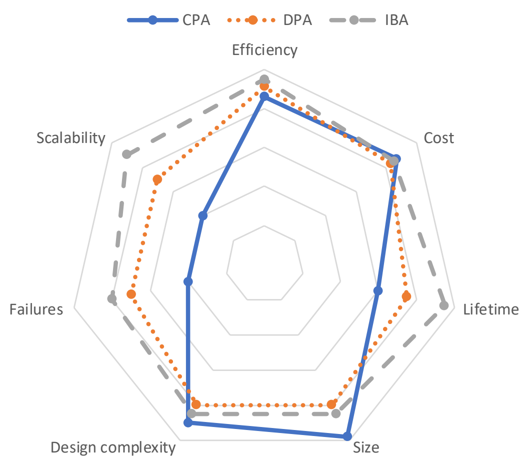



Fig. 5: Radar plot of the architectures

According to table I and figure 5, an intermediate bus architecture with a multiphase buck converter as the point of load is selected for the power distribution system. The intermediate voltage stage keeps the transfer ratio low in order to reduce losses. The multiphase buck converter with four phases reduces the output voltage ripple to a quarter of that of a single buck converter. Another positive effect is the fast transient response of a multiphase buck converter. The only disadvantage is that the overall efficiency of a multiphase buck converter is reduced. A trade-off must be found if the efficiency is to be high or a constant output voltage in combination with a fast transient response are desired.

## III. Design of the Power Distribution System

This section describes the design process of the power distribution system, starting with the design requirements, the hardware design and the software design.

### A. Requirements

To ensure the development of an effective power distribution system, several important specifications must be taken into account. The developed system has several design parameters. These are supported input voltage of up to 100 V and to deliver an output power of up to 67.5 W. The intermediate bus voltage is set to 12.5 V to provide sufficient voltage for high current requirements. Six output channels are required for a variety of loads, each of which provides a stable, reliable output voltage of 5 V and a total output current of 13.5 A. Therefore, the residual ripple of the output voltage should not exceed 150 mV. The transient response of the current distribution system should be less than 50 µs.

The printed circuit board (PCB) for this power distribution system should not exceed the dimensions of 100 mm by 80 mm to fit in the desired application. Consequently, the selection and placement of components must be carefully planned to make the most efficient use of space and distribute the temperature for better cooling.

### B. Design overview

Unlike conventional intermediate bus architectures where the PoLs are single buck converters or other DC/DC converters. This IBA uses a multiphase buck converter for six loads and each channel is equipped with a high-side switch to protect the loads from damage. At the same time, a low dropout regulator (LDO) provides a 5 V supply voltage for the internal ICs and an LDO cascaded with the 5 V LDO generates a 3.3 V supply voltage for the main microcontroller.

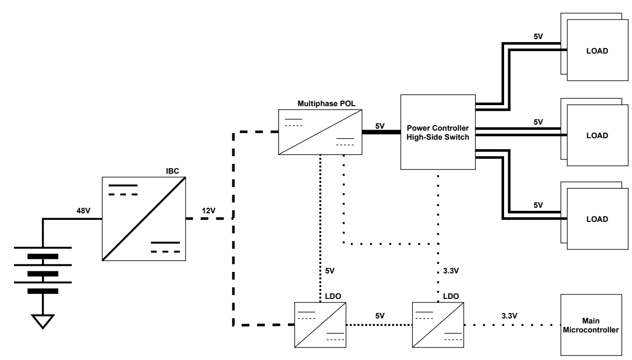



Fig. 6: Overview of the power distribution

As can be seen in figure 6, a Li-ion battery pack with a nominal voltage of 48 V supplies the entire mobile robot with power. The battery is connected to the intermediate buck converter, which regulates the battery voltage down to the intermediate bus voltage of 12.5 V. This voltage supplies the multiphase buck converter and the first LDO, which regulates down to 5 V. The 5 V of the first LDO supplies the power stages for the multiphase buck converter. Most ICs have a supply voltage of 3.3 V, so the second LDO converts the 5 V to 3.3 V. The supply voltage of 3.3 V is required for the main microcontroller, the power controller, the multiphase controller and the analog-to-digital converter (ADC) for current measurements.

Figure 7 shows the 3D plot of the real designed power distribution system on a printed circuit board. The main areas are shown with red rectangles, the intermediate bus converter, the main microcontroller with the LDOs, the multiphase buck

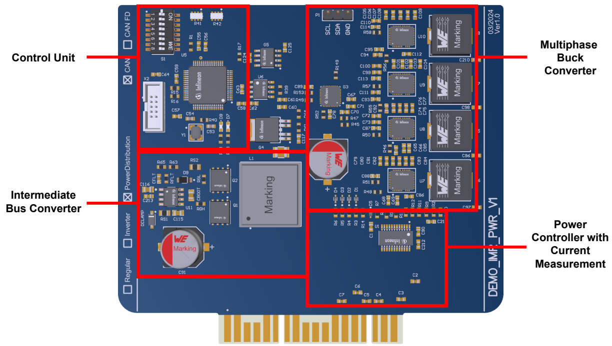



Fig. 7: Overview of the designed power distribution system

converter and the power controller in combination with the ADC and shunt resistors.

There is a so-called edge connector on the underside, which connects the power distribution board to the loads.

*C. Hardware design*

In this subsection, three main areas are covered in more detail, namely the intermediate bus converter, the multiphase buck converter and the power controller.

*1) Intermediate Bus Converter:* The first stage on the power distribution board is the IBC. Here the voltage is stepped down from 48 V to the intermediate voltage level of 12.5 V. Therefore, a non-isolated synchronous buck converter with two external MOSFET switches is used, this can be seen in figure 8. Both the buck converter and the MOSFETs can handle an input voltage of up to 100 V and deliver a nominal output power of 72 W.

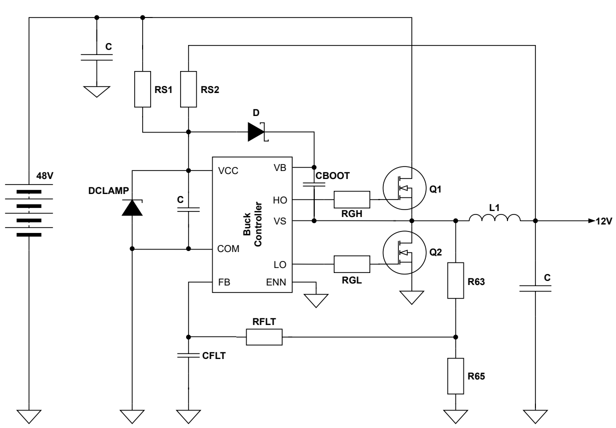



Fig. 8: Overview of the designed IBC [11]

The buck converter is initially supplied via the input voltage through the resistor *RS1* until the buck converter IC starts switching the low-side and high-side MOSFETs. After a few switching cycles, the buck converter IC is supplied via the output voltage 12.5 V with the resistor *RS2*. The values of *RS1* and *RS2* have been carefully designed to deliver the expected 10 mA to the *VCC* pin of the IBC. This approach improves the efficiency of the buck converter due to the voltage difference between the input and output voltage at the *VCC* pin.

The output voltage is regulated to 12.5 V using the *FB* pin. A resistor divider ensures that the expected 500 mV voltage oscillates to the *FB* pin, which is filtered with a low-pass filter. The buck converter has a time-delayed hysteretic method for controlling the average load current [11].

*2) Multiphase Buck Converter:* In this multiphase buck converter (MBC), four phases are used to generate a stable output voltage of 5 V for the loads, which are supplied with 12.5 V via the IBC, like figure 9 depicts. A multiphase buck converter consists of four power stages connected in parallel. The number of power stages varies depending on the power requirement and the desired stabilization of the output voltage ripple. This multiphase buck converter has an input voltage range of 8 V to 16 V for optimal operation. Therefore, all components surrounding the multiphase buck converter are designed up to 25 V instead of 100 V. This reduces the overall size of the components. [12]

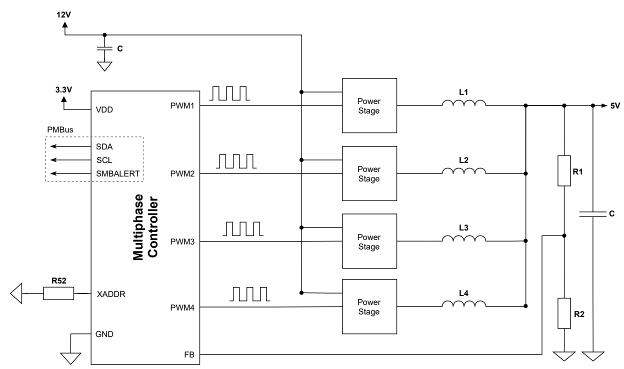



Fig. 9: Overview of the designed multiphase buck converter [12]

The multiphase buck converter has a multiphase controller that ensures communication with the main microcontroller. The multiphase controller generates phase-shifted pulse width modulation (PWM) signals for each phase and has multiple general purpose inputs/outputs (GPIOs) for monitoring and sensing. Four power stages, which are small step-down converters. Each power stage has internal MOSFETs with current and temperature sensing, phase current balancing and multiple fault detection. An inductor is required for each power stage. Before the inductance is selected, the switching frequency must be determined. The power stage can handle switching frequencies from 200 kHz up to 1.5 MHz. A compromise must therefore be found between fast transient response and power losses. Consequently, a switching frequency of 625 kHz is selected in order to achieve the best solution for fast transient response and power losses. [12] [13]

To obtain the desired output voltage of 5 V, a network resistor must be inserted between the output node and the feedback pin of the multiphase buck converter. A ratio must be calculated across the network resistor $R_{1,MBC}$ and $R_{2,MBC}$

to set the output voltage to 5 V. To avoid disturbing the control loop, a small resistor value is used for $R_{1,MBC}$ and $R_{2,MBC}$. For $R_{1,MBC}$ the value is 200 Ω. Equation 1 is used to calculate $R_{2,MBC}$.

$$V_{set,MBC} = V_{out,MBC} \cdot \frac{R_{2,MBC}}{(R_{1,MBC} + R_{2,MBC})} \tag{1}$$

Solving equation 1 for $R_{2,MBC}$ yields the value for $R_{2,MBC} = 68\,\Omega$. Equation 2 is used to calculate the inductance for a single phase.

$$L_{MBC} = \frac{V_{out,MBC} \cdot (1 - D_{MBC})}{f_{sw,MBC} \cdot \Delta I_{L,MBC}} \tag{2}$$

Here $V_{out}$ is the output voltage, $D_{MBC}$ the duty cycle, $f_{sw,MBC}$ the switching frequency and $\Delta I_{L,MBC}$ the current ripple for a single phase. The duty cycle is calculated using equation 3. [13]

$$D_{MBC} = \frac{V_{out,MBC}}{V_{in,MBC}} \tag{3}$$

The target ripple is set to 40 % to meet the requirements and can be calculated by equation 4. [13]

$$\Delta I_{L,MBC} = 0.4 \cdot I_{ph,max} \tag{4}$$

Equation 5 is used to calculate the input capacitance for each phase. [13]

$$C_{in,ph} = \frac{I_{ph,max} \cdot D_{adj} \cdot n \cdot (1 - D_{adj})}{f_{sw,MBC} \cdot \Delta V_{in(DC)}} \tag{5}$$

$D_{adj}$ is the adjusted duty cycle and is calculated using equation 6. [13]

$$D_{adj} = \frac{V_{out}}{V_{in}} \cdot \eta_{target} \tag{6}$$

$\Delta V_{in(DC)}$ is the DC voltage ripple to be expected at the input. Depending on the IBC, the $\Delta V_{in(DC)}$ can vary, but it is usually around 200 mV to 500 mV peak to peak. $\eta_{target}$ is the target efficiency to be expected and is set to 90 %, which is a realistic value for a multiphase buck converter. [13]

Equation 7 is used for the output capacitance per phase. [13]

$$C_{out,ph} = \frac{I_{pp,L}}{8 \cdot f_{sw,MBC} \cdot \Delta V_{out,DC}} \tag{7}$$

$I_{pp,L}$ is the inductor ripple current worst case scenario by taking the used inductance $L_{MBC} = 3.3\,\mu$H into account. [13].

In table II the chosen values for the multiphase buck converter can be depicted.

TABLE II: Multiphase buck converter decided parameters

| Parameter | Value | Description |
|---|---|---|
| $L_{MBC}$ | 3.3 µH | Inductance |
| $C_{in,total}$ | 42 µF | Total input capacitance |
| $C_{out,total}$ | 22 µF | Total output capacitance |
| $R_{1.MBC}$ | 200 Ω | Network resistor 1 |
| $R_{2,MBC}$ | 68 Ω | Network resistor 2 |

*3) Power Controller:* A multichannel power controller, like figure 10 shows is used to distribute the power to all six loads. This IC replaces electromechanical relays, fuses and discrete circuits. This device uses a serial peripheral interface (SPI) to communicate with the main microcontroller. The IC is supplied with the 5 V from the multiphase buck converter to the *VS* pin. The digital supply voltage (*VDD*) for the power controller IC is set to 3.3 V by the second LDO. The power controller supports three channels with a nominal output current of 3 A and the other three channels with a nominal output current of 1.5 A. Each channel has an integrated internal current measurement that can be read out via the pin *IS*. This pin outputs an analog signal that is connected to a *ADC* pin of the main microcontroller. A shunt resistor for current measurements and a low-pass filter network are connected between the *IS* pin of the power controller and the *ADC* pin of the main microcontroller. This low-pass filter is required for accurate current measurement. The channel to be monitored is selected by the software. [14]

Several warning and error functions are integrated into the power controller. If an overvoltage, undervoltage, short-circuit or over temperature fault occurs, the power controller switches off the corresponding channel or all channels immediately. [14]

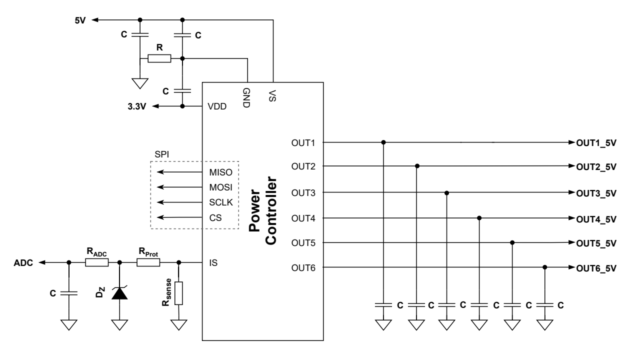



Fig. 10: Overview of the designed power controller [14]

All six channels can be activated or deactivated independently of each other via the SPI. The power controller is a so called high-side switch. This means that the load is protected by this device in the event of a short circuit, for example.

### D. Software

This subsection describes the coding procedure for the power distribution system including the flowchart in figure 11.

First, all components must be initialized together with the state machine. All settings are made during this initialization, e.g. current measurement ratio, restart behavior in the event of errors, timing and much more.

Secondly, when everything is initialized, the program switches to the next state, *STATE_IDLE*. In the idle state, the program checks whether the multiphase buck converter and the power controller are ready for use. The program also checks whether an error has occurred. If so, the next state is *STATE_RESET* and if not, the next state is *STATE_RUN*. In the run state, the program reads the current measured values, the states of the individual components and whether an error has occurred. If there is an error or a warning, this error is first deleted by switching to the *STATE_RESET* state and then read out again. If the error occurs ten times, the state changes from *STATE_RESET* to *STATE_STOP*. In this state, the entire system shuts down.

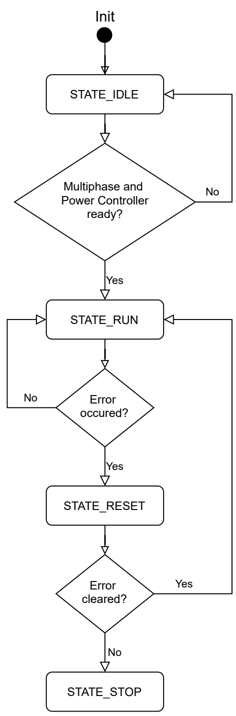



Fig. 11: Flowchart of the power distribution system

## IV. Results

In this section, measurements are carried out on the power distribution panel. Several measurements and tests were carried out to ensure the functionality of the power distribution system. Communication tests with all components, including CAN communication to communicate with the entire mobile robot. Protection tests such as short circuit, over or under voltage and over temperature were performed. In the next sections, the test setup is shown and the main functionalities of the multiphase buck converter are demonstrated. At the end, the current efficiency graph of the entire power distributor board is shown.

### A. Measurement setup

To perform a functional test for all six channels, the measurement setup is shown in figure 12. The input voltage of the power supply is set to $48\,\mathrm{V}$. Three power resistor blocks of $3.3\,\Omega$ and $10\,\Omega$ each are used. Some power resistors are connected in parallel to achieve a higher output current. One output channel is connected to the electronic load. A constant output current can be manually adjusted with the electronic load. Six multimeters are connected directly after the output channels to measure the output current. The output voltage is measured with the oscilloscope directly at the output channels on the circuit board.

The efficiency is also measured with this setup. The current was adjusted by turning on the loads. For each output channel, the current flowing through the power resistors was different due to the availability of the resistors.

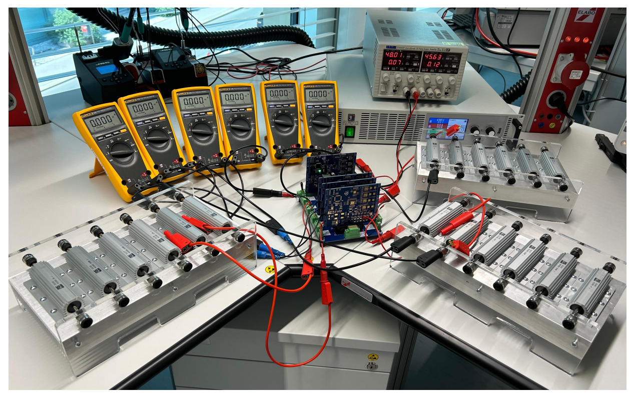


Fig. 12: Measurement setup to test all six channels simultaneously

### B. Measurement results

The first measurement on the MBC is the output voltage ripple and the output current. Here two power resistors of $3.3\,\Omega$ are connected in parallel and act as a load. The voltage probes of the oscilloscope are connected directly to the output capacitor of the MBC. Depending on the load, the multiphase controller switches the phases on or off. In this case, measurement without load 13b, the MBC operates in single-phase mode, and with load 13a, all four phases are activated manually via the software. The waveforms in figure 13 clearly show the difference. The detailed results are listed in table III.

TABLE III: Measurement results of the MBC

| Parameter | Value | Unit |
|---|---|---|
| $V_{out\_max\_wl}$ | 5.04 | V |
| $V_{out\_min\_wl}$ | 4.96 | V |
| $V_{out\_mean\_wl}$ | 5.00 | V |
| $V_{out\_pp\_wl}$ | 81.7 | mV |
| $V_{out\_max\_nl}$ | 5.06 | V |
| $V_{out\_min\_nl}$ | 4.94 | V |
| $V_{out\_mean\_nl}$ | 5.00 | V |
| $V_{out\_pp\_nl}$ | 125.3 | mV |

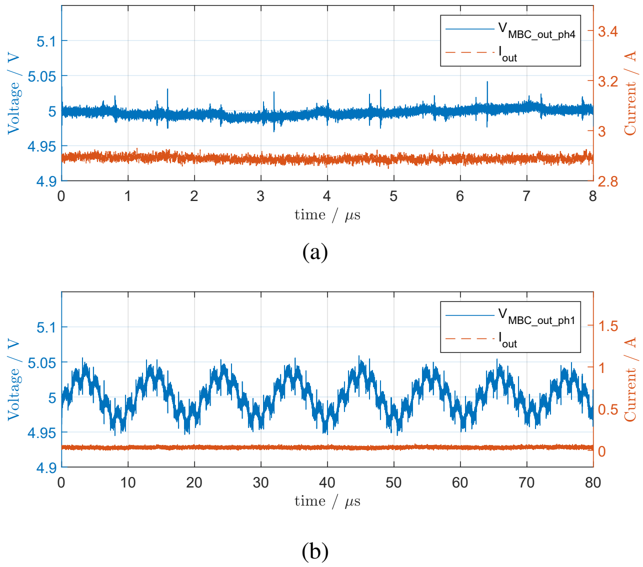



Fig. 13: Output voltage ripple of the MBC with load (a) and without load (b)

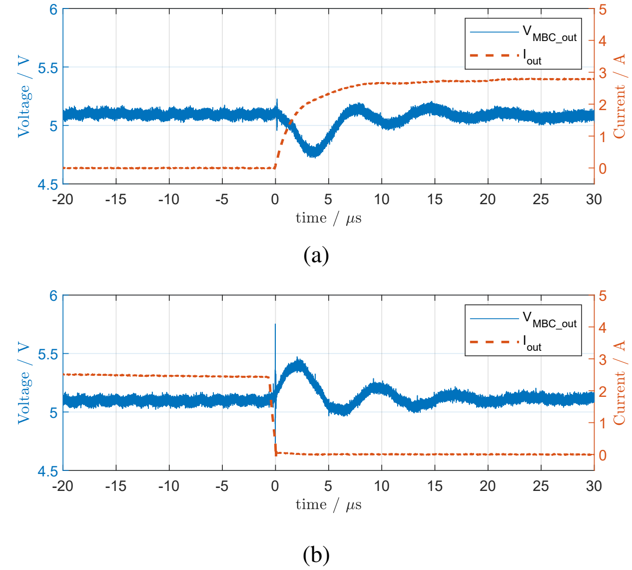



Fig. 14: Output voltage transient response with a load step from 0 A to 3 A (a) and with a load step from 3 A to 0 A (b)

The next measurement is the transient response of the MBC. The cables connected to the motherboard are immediately connected and disconnected to simulate a load step. In figure 14, the figure 14a shows a load step from 0 A to about 3 A. The load change results in a drop in the output voltage, which then stabilizes very quickly. The reason for this is that the energy stored in the capacitors is discharged in a very short time and the inductor current immediately recharges the capacitors. This takes some time, so an undershoot occurs. The control loop also has an effect, depending on how quickly it detects the change and adjusts the duty cycle. This is why conventional multiphase buck converters operate at a higher switching frequency. [13]

The figure 14b shows a load step from 3 A to 0 A. This causes the output voltage to overshoot. In this case, the energy generated in the inductor that is no longer needed after the load step must be stored somewhere, which charges the output capacitors and causes an overshoot. [13]

The table IV shows the result of a load step. The transient time $t_{response}$ is measured with the oscilloscope.

TABLE IV: Measurement results of the transient response of the MBC

| Parameter | Value | Unit |
|---|---|---|
| $V_{out\_max\_top}$ | 5.23 | V |
| $V_{out\_min\_top}$ | 4.72 | V |
| $V_{out\_pp\_top}$ | 506.9 | mV |
| $t_{response}$ | ≈25.00 | µs |
| $V_{out\_max\_bot}$ | 5.75 | V |
| $V_{out\_min\_bot}$ | 4.73 | V |
| $V_{out\_pp\_bot}$ | 1.02 | V |
| $t_{response}$ | ≈23.00 | µs |

The last measurement discussed here is again a load step, but now the MBC is configured by adding and removing phases autonomously. The configuration is done with the software and is as follows. Each phase is added with each amp and vice versa. At an output current of 3 A all four phases are activated. If no load is connected, the MBC operates in single phase mode. An electronic load from *EA Elektro-Automatik* is used to generate a load step. A constant output current of 3 A is set on one channel of the power distribution board. The output voltage probes are connected directly to the output capacitors of the MBC.

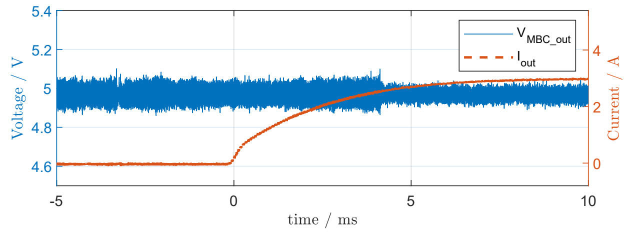
The figure 15 clearly shows the autonomous addition and removal of phases during a load step. In the figure 15a, all four phases are activated at a time of 4.2 ms and the current reaches almost 3 A. As it can be seen, the load step does not occur immediately, but it looks as if a capacitor is being charged. Therefore, there is no undershoot during this transition. The figure 15b shows the falling phase condition. The electronic load is turned off and the phases are turned off at a time of 400 µs.

To demonstrate the efficiency of the designed power distribution system, the appropriate measurements are performed. The power supply is set to 48 V, the power distribution board is connected to the motherboard, all six channels are activated and connected to a load. The power supply is used to measure input voltage and input current. Another six multimeters are connected to the output side of each channel where the current is measured. The output voltages are measured on the oscilloscope. The following currents are then adjusted.

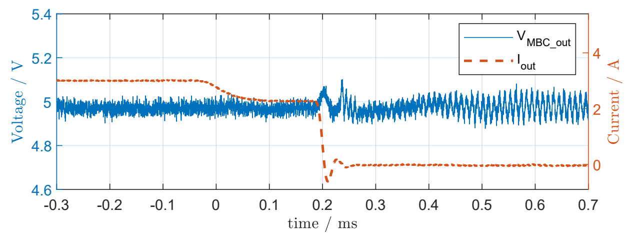
The overall efficiency versus current curve is shown in figure 16.

## V. Conclusion

This paper outlines the design and theory behind power distribution systems, comparing centralized, decentralized,




(a)




(b)

Fig. 15: Output voltage with a load step from 0 A to 3 A (a) and with a load step from 3 A to 0 A (b)

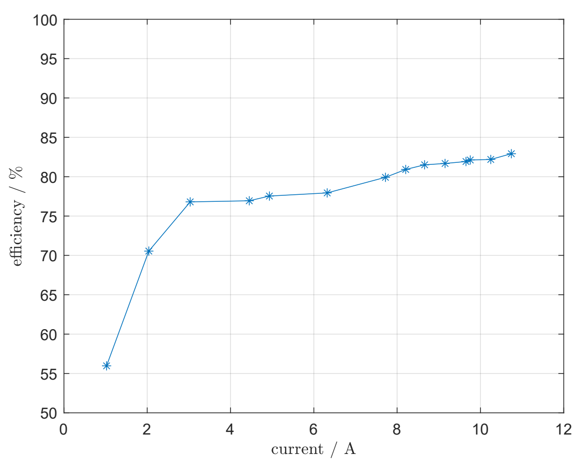



Fig. 16: Current-efficiency measurement curve

and intermediate bus architectures. It examines the benefits and considerations of each architecture, starting from system requirements to component selection, and detailing both hardware and software design. Several measurements were performed. The result is a modular power distribution system with a wide input voltage range, low output voltage ripple and fast transient response. Key features include a multiphase buck converter as the Point-of-Load (PoL) and a high-side switch for load protection.

Further improvements are needed to enhance overall efficiency, including detailed analysis of the intermediate bus converter's switching behavior and accurate simulations of the multiphase buck converter. Additionally, implementing intelligent switching for the six output channels based on power demand requires further programming and testing.

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